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TESTS TO DETERMINE THE ULLAGE EXPLOSION TOLERANCE OF HELICOPTER FUEL TANKS

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Twenty-one ballistic tests were conducted on fuel tanks similar to those on US Army helicopters to determine their ability to withstand pressures generated during an ullage explosion. The tanks were filled with known JP-4/air gas mixtures and impacted with caliber .30 M1 incendiary projectiles at approximately 2000 feet per second. The pressure rise was measured with transducers and the tank response was recorded with high-speed photography. The results indicated that noncrashworthy bladder tanks in honeycomb structure have an overpressure threshold of about 20 psig, while crashworthy tanks in Z-bar reinforced aluminum structure can tolerate explosive

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pressures to about 60 psig. The results can be useful in the design of optimum ullage protection schemes for the armor piercing incendiary (API) combat threat.

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BACKGROUND

One of the key design criteria necessary to determine the optimum fuel system design for combat survivability is an understanding of the tank response to dynamic internal pressures as the result of ullage explosion. Impacts by both high-energy inert projectiles and high-explosive projectiles can generate sufficient internal pressure to catastrophically destroy fuel tanks and surrounding structures. Considerable effort has been expended to examine the hydraulic ram phenomenon and develop techniques to predict and minimize its effects. Comparatively little effort has been expended to determine helicopter fuel tank response to pressures that are generated during an ullage explosion.

The fundamental question that must be answered is whether or not an internal explosion in the ullage will cause sufficient damage to "kill" the aircraft. The occurrence of the explosion would be predicated on the existence of a flammable fuel/air vapor and the presence of a sufficient ignition source. The magnitude of the explosion would generally be a function of the ullage volume and the specific fuel/air ratio. The aircraft response would depend on the strength of the fuel container and tank structure as well as its relationship to critical structure and components.

Previous Army research efforts show that flammable fuel/air mixtures exist in Army helicopter fuel tanks under almost all flight conditions, and that ignition of this vapor is a virtual certainty when exposed to combat threats. Reference 1 contains empirical data which indicates that explosions of JP-4/air mixtures can generate pressures up to 90 psig. The lack of data on the fuel tank response to explosive pressure makes complete analysis of this failure mode inexact.

The absence of this data in the past has not seriously hampered vulnerability reduction design and analysis, since protection concepts were evaluated on the complete prevention of ullage reaction. However, recent ullage vulnerability reduction schemes are such that system penalties can be reduced significantly if the protection level is relaxed to the point where "small" explosions are permitted. For example, Reference 2 shows that the membrane nitrogen inerting system weight can be reduced approximately 30 percent by designing for a maximum oxygen concentration of 12 percent in lieu of 9 percent. At the 12-percent level some ullage explosion is possible, but a pressure peak substantially less than 90 psig will result. If the tank retains its integrity the reactions will be self-extinguishing due to lack of oxygen. If it tears, fuel spillage and catastrophic fire will

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[1] Clodfelter, R. G., and Ott, E. E., Capt, USAF, *Preliminary Investigation of Fuel Tank Ullage Reaction During Horizontal Gunfire*, AFAPL-TR-72-55, Air Force Aeropropulsion Laboratory, Wright-Patterson Air Force Base, Ohio, November 1972.

[2] Manatt, S. A., Buss, L. B., and Funk, A. F., *Design Criteria for Application of Membrane Nitrogen Inerting Systems to Army Aircraft Fuel Tanks*, USARTL-TR-77-50, Applied Technology Laboratory, US Army Research and Technology Laboratories (AVRADCOM), Fort Eustis, Virginia, December 1977, AD A052869.

result. If the capability of the tank to tolerate internal explosions were known, the maximum oxygen limit could be established to permit optimum design of the membrane inerting system. Furthermore, if the fuel tank design parameters that influence over-pressure tolerance were understood, overall design of optimum fuel tank ullage protection could be realized.

The basic objectives of these tests were to begin to quantify the tolerance of typical helicopter fuel tanks to ullage explosions and to identify those design parameters that influence this failure mode.

APPROACH

The major factors that determine the outcome of an ullage explosion appear to fall into two categories. The first category includes the physical characteristics of the container itself—the ultimate structural strength of the tank, dynamic response to transient pressure induced loading, surface-to-volume ratio, bladder strength, geometry, and venting. The second is the explosion itself, including primarily the magnitude and rate of the pressure rise and the location of ignition and flame fronts.

No existing data was found to assist in reducing the variables or selecting test configurations. It was decided as a first step to examine a representative number of typical Army helicopter fuel tanks to obtain an overview of overpressure tolerance levels and to make observations concerning relationships between design variables. For maximum validity these tests would be conducted on actual aircraft or aircraft sections under realistic conditions.

Several fuel tanks were available for use on this program which appeared to offer the desired variety of construction: two UH-1B aircraft fuel tanks, one UH-1H aircraft fuel tank, one AH-1 fuel tank, and several fuel tank cubes manufactured in accordance with MIL-T-27422B. A schematic diagram of each test tank configuration is shown in Figure 1. The UH-1B and AH-1 tanks used in this test have honeycomb structure around noncrashworthy bladders, the UH-1H contains a complete crashworthy fuel system, and the fuel tank cubes are made of crashworthy material and fit a fixture that accommodates Z-bar reinforced aluminum structure.

Each configuration would be tested by filling the tank with a combustible fuel/air mixture and igniting it with an incendiary projectile. There would be no liquid in the tank to sustain the fire should the tank rupture. The fuel/air ratio would be at or near optimum, and the pressure-time history would be obtained with pressure transducers.

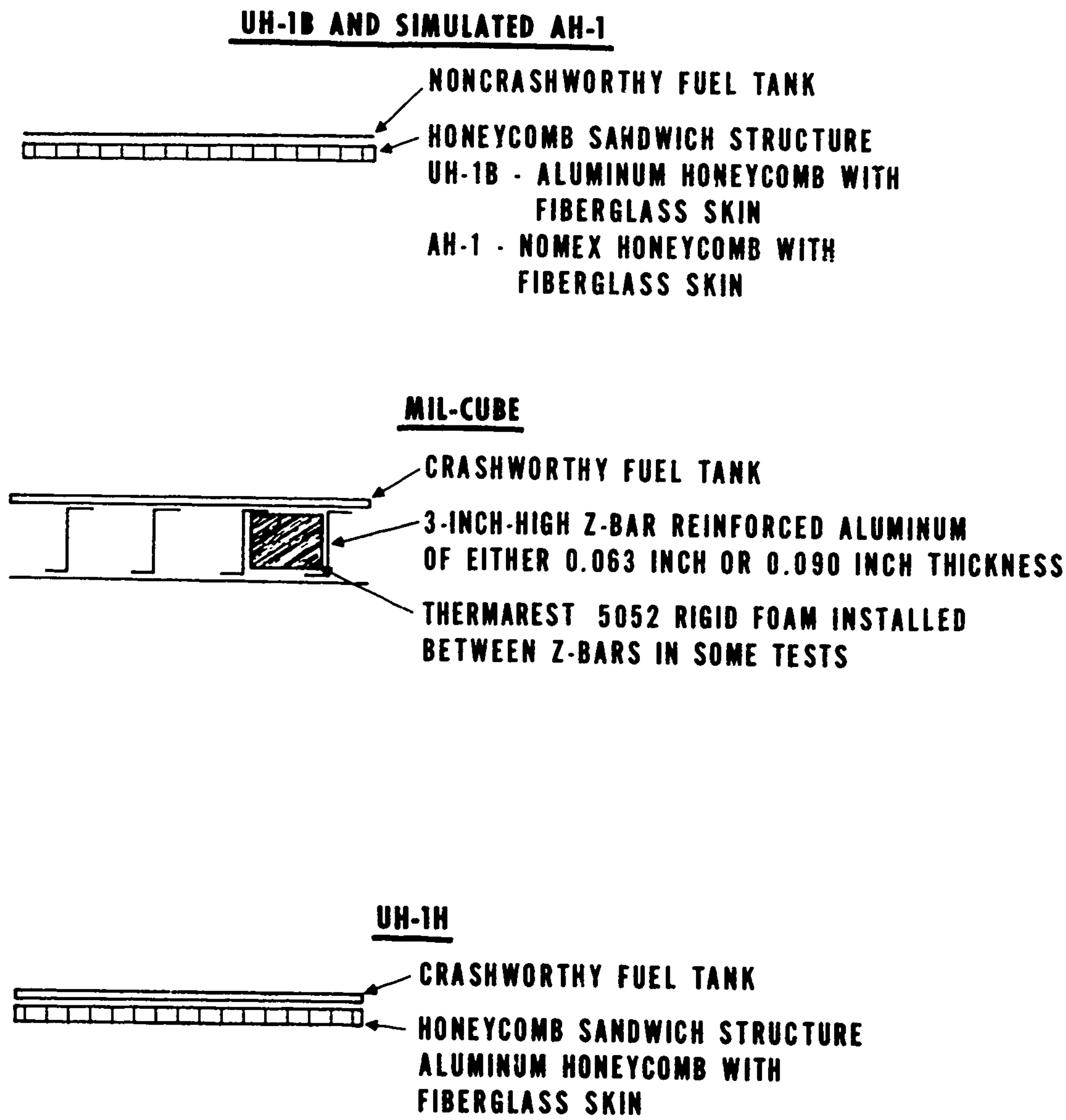

Figure 1. Schematic diagram of fuel tank configurations tested for combustion overpressure tolerance.

TEST PROGRAM

APPARATUS

The apparatus used to inject the fuel vapors, measure the ullage concentration, and record the data was the same for each shot. A vapor-generating tank was used as shown in Figure 2 to provide a JP-4/air mixture to the test tank. The fuel/air ratio was monitored with an MSA Lira Infrared Analyzer.* Sufficient control of the fuel/air ratio was achieved by controlling the temperature of the JP-4 liquid in the generating tank. Provisions were made in each test tank for disconnecting the generating tank prior to the shot.

Kulite model HKS pressure transducers were used and the data was recorded and processed using the equipment shown in Figure 3. Thermocouples were used to monitor the ambient, test tank, and vapor-generating tank temperatures. Velocity screens and a Hewlett-Packard Model 5304 frequency counter were used to measure the projectile velocity. Grid paper placed over the impact point provided time of impact data to the instrumentation.

Two Photosonics high-speed (600 frames per second) cameras and one Arriflex camera at normal speed were used during each test. Still photographs were taken before and after each test.

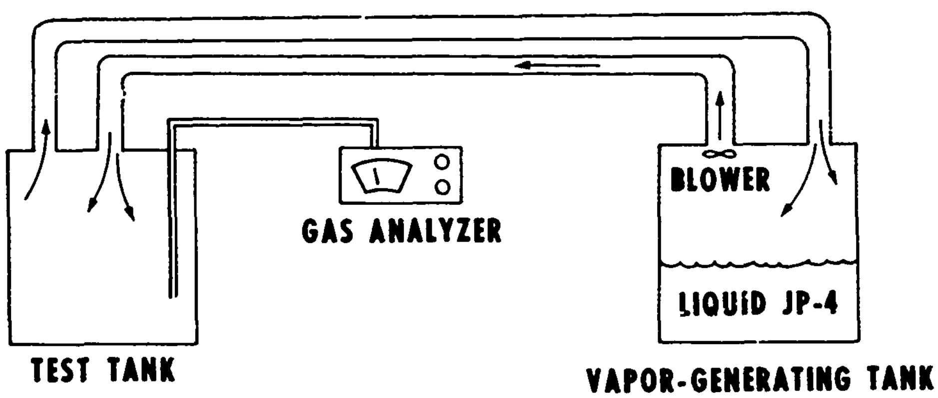

Figure 2. Schematic diagram of vapor-generating and sampling system.

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*This analyzer measured the fuel/air ratio as volume percent JP-4 vapors in air. Therefore a volumetric fuel/air ratio of 0.10 was indicated as 10 percent. Throughout this report volume percentage will be used to indicate the concentration of JP-4 in the JP-4/air mixture.

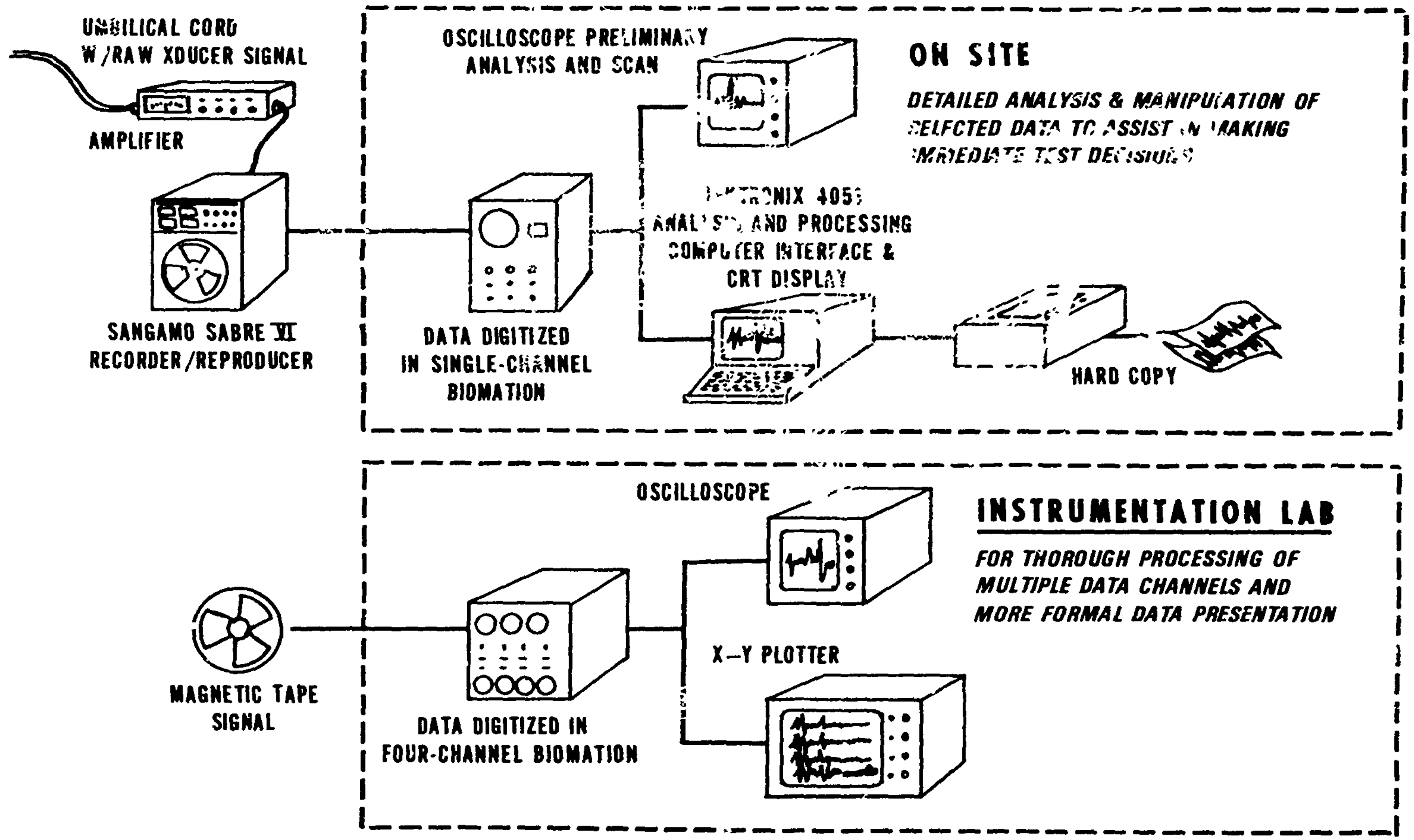

Figure 3. Schematic diagram of data acquisition/processing equipment.

PROCEDURE

The pressure transducers, vapor transfer lines, and vapor sample lines were attached to the tank. The JP-4 fuel in the vapor-generating tank was conditioned to 80°-90°F. The fan was turned on and a vapor circulation was established between the vapor-generating and test tanks. This procedure generally established a uniform fuel/air mixture in the test tank between 1 and 2 percent JP-4 by volume.* The vapor transfer and sample lines were then disconnected from the tank and the holes were sealed with 0.090-inch-thick sheet aluminum. The vapor-generating tank and sampling system were moved to a safe distance, and the caliber .30 incendiary M1 projectile (7.62mm bore diameter) was fired at 2000 feet per second into the tank. An aluminum function plate (0.125-inch-thick 2024-T3) was placed directly on the specimen at the impact point to insure adequate and uniform incendiary activation during each test. The time between disconnecting the vapor transfer lines and actual firing was about 5 minutes. Preliminary tests showed that vapor conditions remained stable in the sealed test tank for at least 15 minutes.

UH-1B TESTS

Each UH-1B fuselage tested contained two noncrashworthy Uniroyal 173-15 bladder tanks which are caliber .50 (12.7mm bore diameter) self-sealing in the lower half. The structure is predominately 1/2-inch-thick aluminum honeycomb with fiberglass skins.

The top access cover was removed and modified to accept the vapor transfer tubes and vapor sample line. Transducers were mounted in the top access cover and in the front crossover opening to provide a pressure reading at the top and bottom of the tanks, respectively. The fuel level probes were removed and thermocouples were mounted in the upper and lower ullage. A fuselage with associated test equipment is shown positioned in front of the ballistic backstop in Figure 4.

Three tests were conducted using substantially the same general procedure discussed earlier. Vapor samples were taken at three depths: 6 inches, 18 inches, and 30 inches from the top of the tank. The ambient and ullage temperatures were measured. Each tank was impacted about one-third from the bottom and a 0.125-inch-thick 2024-T3 aluminum plate was taped on the aircraft at that point to insure projectile activation.

During the first UH-1B test the caliber .30 incendiary M1 projectile impacted the left fuel tank at about the one-third level, passed through the function plate and the entire tank structure, and was expended inside the right fuel tank (Figure 5). The resulting overpressure damaged the deck plate and fiberglass subpanel, but aside from the entrance and exit holes, the bladder was undamaged (Figure 6). The transducer in the top of the tank was damaged and provided no data. Pressure measurements from the bottom transducer indicated a peak of 15.9 psig and a rise time of 0.53 second.

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*This mixture, although slightly less than stoichiometric, appeared to result in maximum pressure rise.

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USARTL Technical Note 29

TITLE: Tests To Determine the Ullage Explosion Tolerance of Helicopter Fuel Tanks

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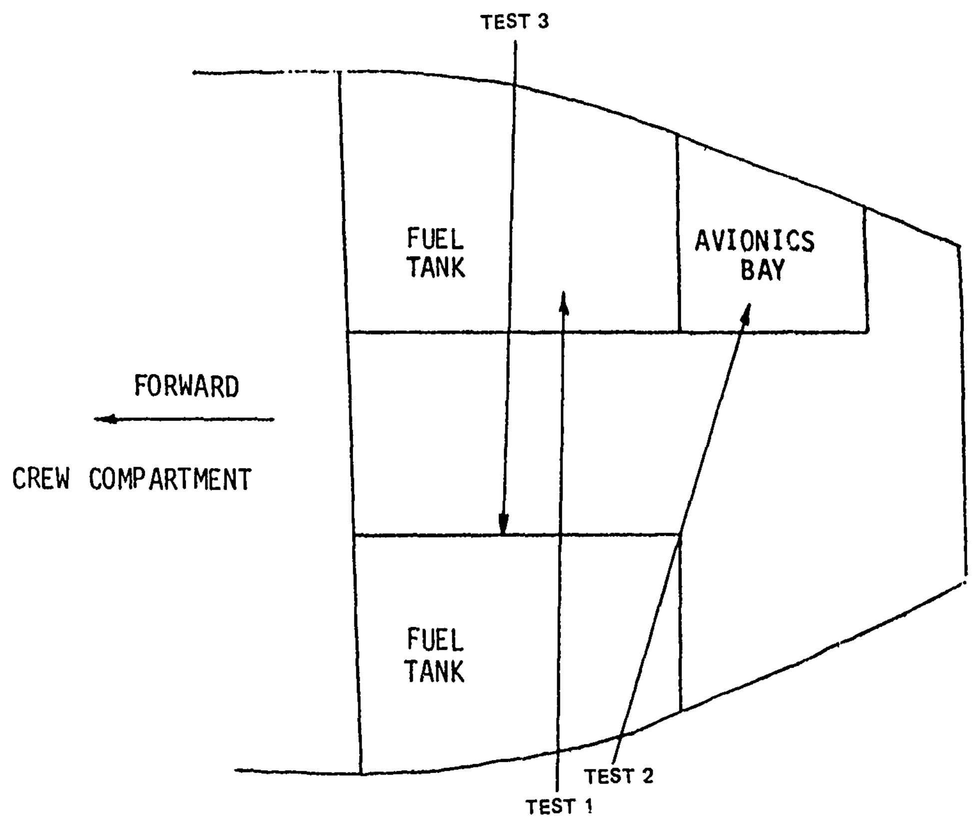

Figure 5. Diagram of projectile flight paths - UH-1B tests.

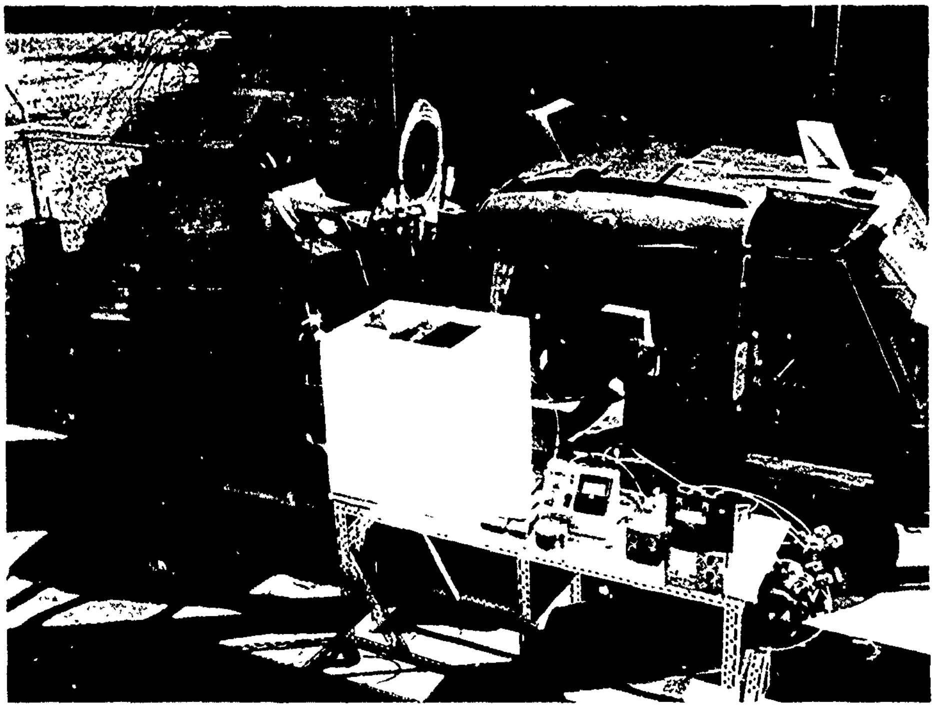

Figure 4. Overall view of typical UH-1B test setup.

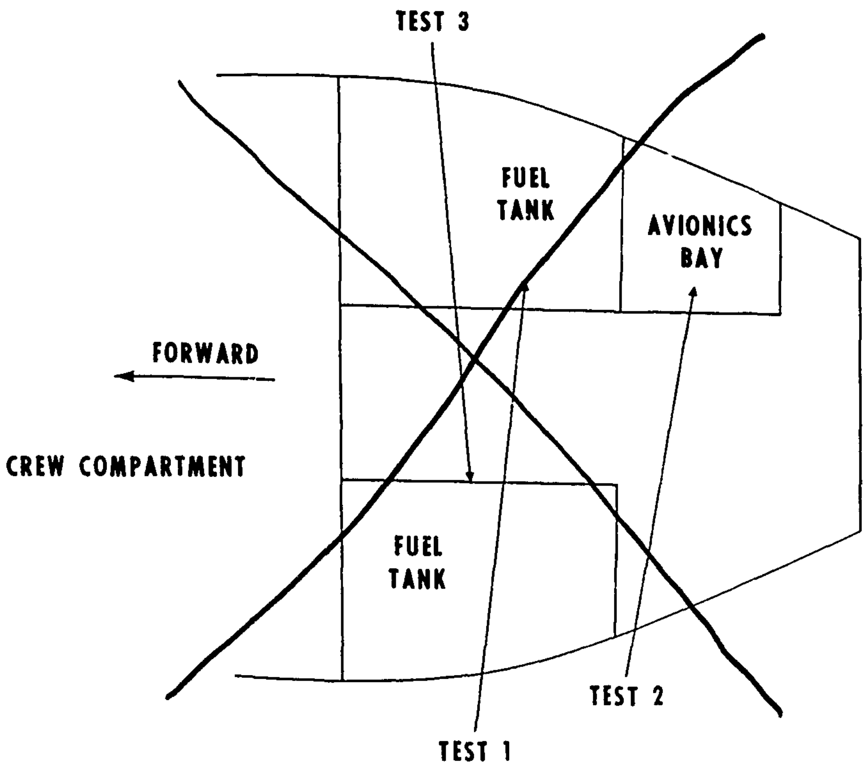

Figure 5. Diagram of projectile flight paths - UH-1B tests.

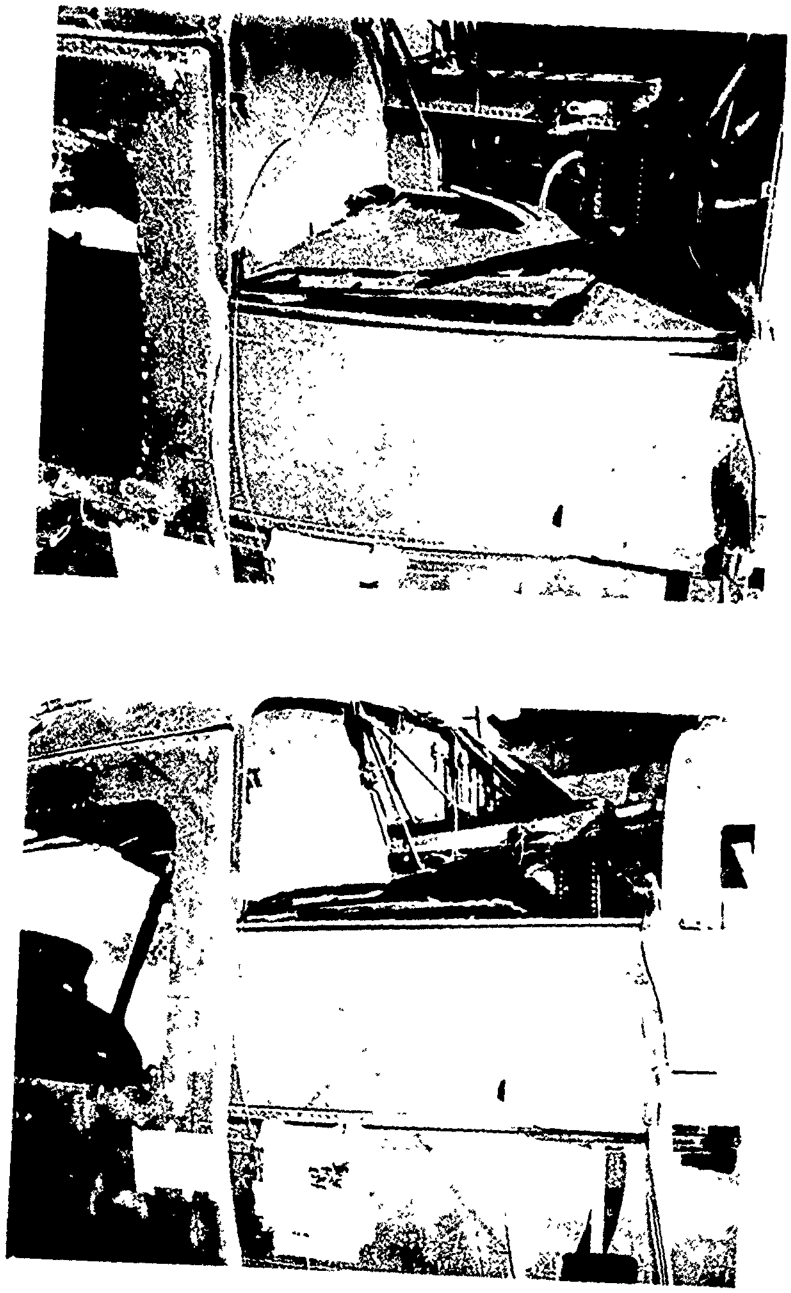

Figure 6. Aircraft damage resulting from the first UH-1B test.

During the second UH-1B test the projectile impacted the left fuel tank, hit the opposite corner, exited the tank compartment, and expended in the left side avionics bay (Figure 5). Black burn marks from the incendiary activation were visible at the entrance and exit sites. The deck was blown off from the explosion and expansion of the bladder. The decking was cracked and the material around the fasteners failed. The fiberglass subpanel sustained some damage but remained substantially intact and continued to support the tank (Figure 7). The damage to the bladder was limited to the entrance and exit holes. The pressure transducers indicated a peak of 21.6 and 21.8 psig, respectively, in 0.22 second.

During the third UH-1B test the projectile impacted the right tank, continued through the tank, and expended between the bladder and tank structure of the left fuel tank (Figure 5). The resulting explosion cracked the deck plate and blew it off except for three fasteners, and the fiberglass subpanel failed around its circumference, permitting the bladder to collapse inward about 5 inches. The oval aluminum tank top was bowed and the upper transducer wire was broken. The bladder was torn on three sides around the top of the tank (Figure 8). The pressure transducer near the bottom of the tank indicated a peak of 23.5 psig in 0.22 second.

The data obtained during the UH-1B testing is summarized in Table 1. The pressure-time histories for those three tests are shown in Figure 9. In general, the readings are somewhat lower than would be expected because of two factors. The bladders were collapsed inward from the tank structure, which effectively lowered the amount of fuel vapors in the container and provided some expansion volume for the bladder. Also, the aft crossover line was deliberately left open on the first two shots in an attempt to minimize the pressure buildup by venting. This line was covered in the third test to permit destructive pressure buildup. Note that the shape of the pressure trace on the third test is different from the shapes of the first two tests. The pressure is still rising when bladder failure occurs, resulting in a sharp drop-off.

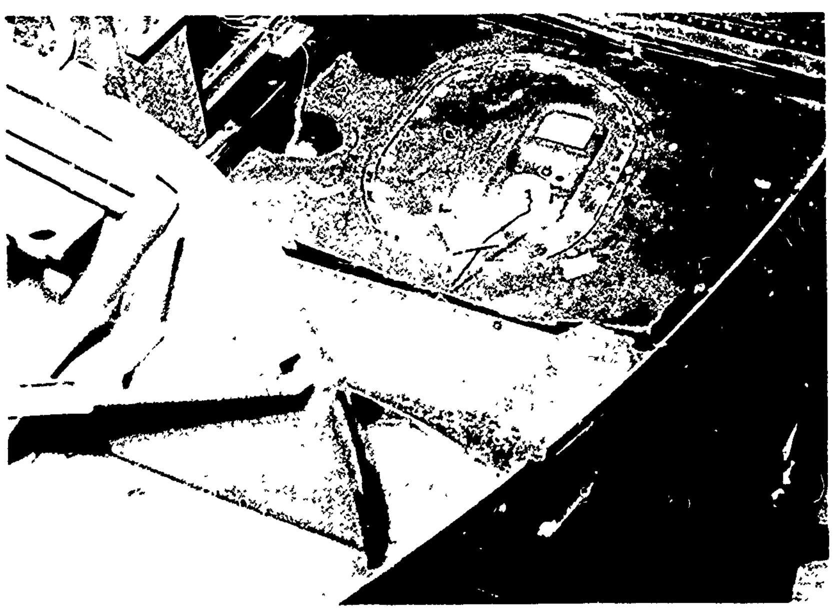

Figure 7. Aircraft damage resulting from the second UH-1B test.

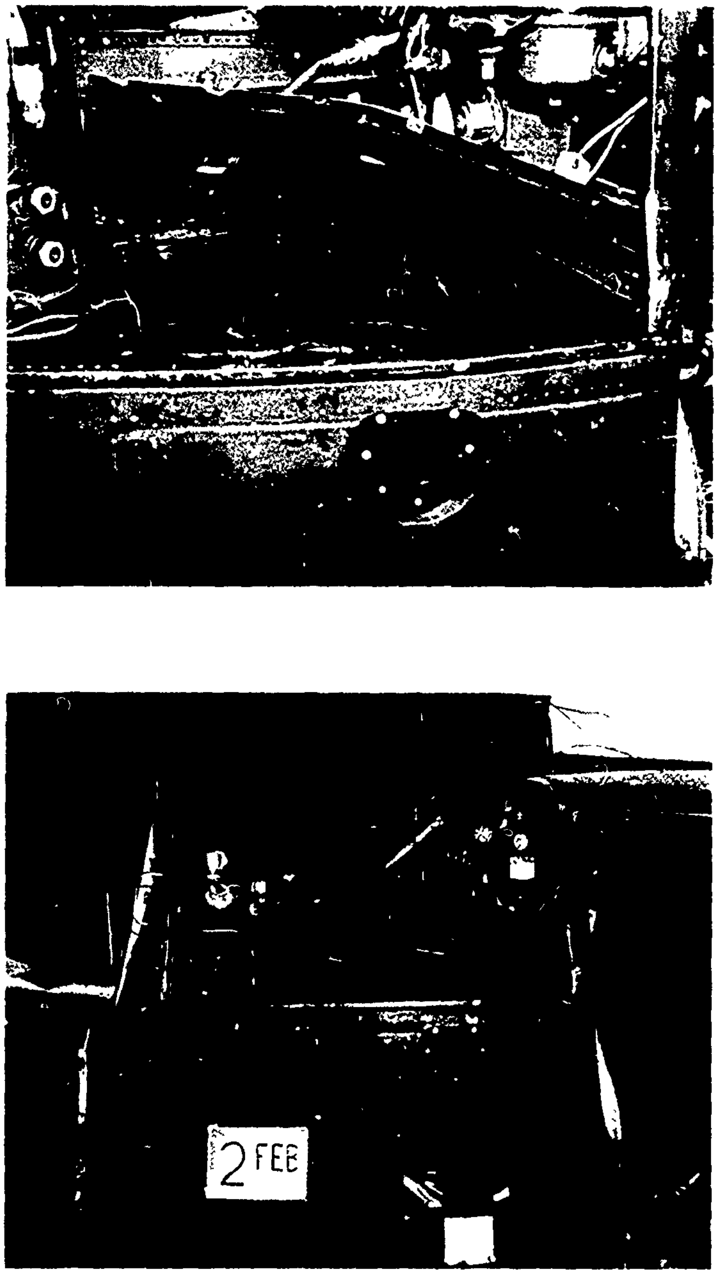

Figure 8. Aircraft damage resulting from the third UH-1B test.

TABLE 1. RESULTS OF UH-1B TESTS

Test No.	Ambient Temperature (^{o}F)	Ullage Temperature (^{o}F) U	L	Fuel/Air Mixture (volume % JP-4) U	L	Pressure Rise (psig) U	L	Time to Peak (sec) U	L
1	56	67	68	1.3	1.45	*	15.9	*	0.53
2	46	51	50	1.1	1.2	21.6	21.8	0.22	0.22
3	34	60	69	1.0	1.0	**	23.5	**	0.22

U - Upper part of tank
L - Lower part of tank
* - Transducer damaged; no data
** - Transducer line cut by damaged structure; no data

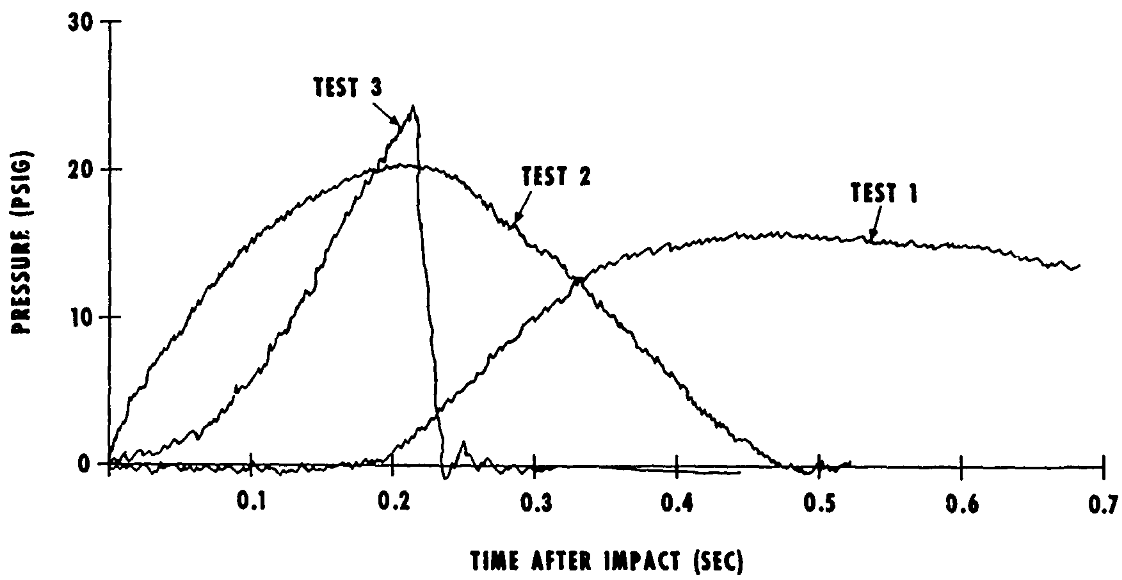

Figure 9. Pressure-time histories obtained during UH-1B fuel tank ullage overpressure tolerance tests.

AH-1 TEST

A fixture that is similar to the structure around the AH-1 forward tank was used in this overpressure testing. Since four of the structural panels had been damaged in previous testing and no actual AH-1 panels were available, 1-inch-thick NOMEX honeycomb panels were used. They were the lower panels on the front, right, left, and aft sides. A top for the structure was made from 5/8-inch-thick plywood reinforced by 2-inch by 4-inch lumber. The structure contained a Uniroyal noncrashworthy bladder that was caliber .50 self-sealing in the lower half. Transducers were mounted in the top and front of the tank. The top plate was modified to permit hookup of the vapor transfer and sample lines. All other tank openings were blocked with 1/4-inch-thick aluminum plates.

The tank was filled with a uniform 1 percent JP-4 by volume mixture. The caliber .30 incendiary at 2000 feet per second passed from left to right through the middle of the tank, initiating an explosion that blew off the tank top and tore the bladder across the top (Figures 10 and 11). The lower side panels were also cracked at projectile entrance and exit sites (Figures 12 and 13).

The pressure-time histories obtained during the test are shown in Figure 14. The top transducer cable was severed by failing structure during the explosion and did not provide a complete history. However, it seems to parallel the reading of the front transducer, which indicated bladder failure at 25.5 psig, 0.125 second after impact. Note that this pressure corresponds closely to the pressure at failure of the UH-1B bladder tank.

Figure 10. Damage to top of simulated AH-1 structure.

Figure 11. Damage to AH-1 bladder tank.

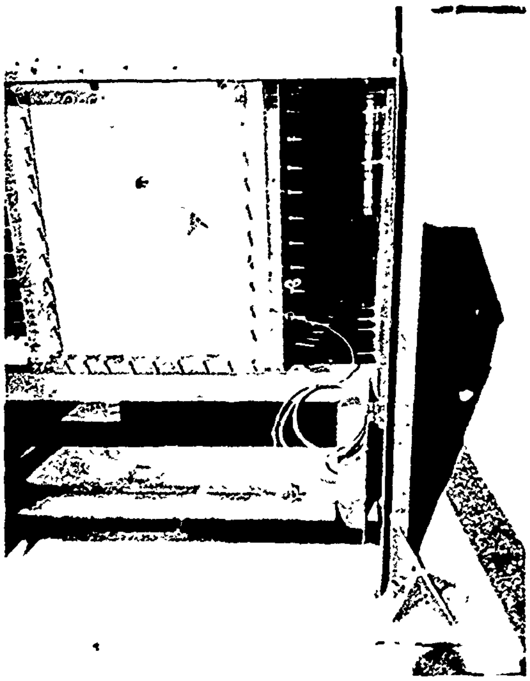

Figure 12. Damage to simulated AH-1 structure at projectile entrance.

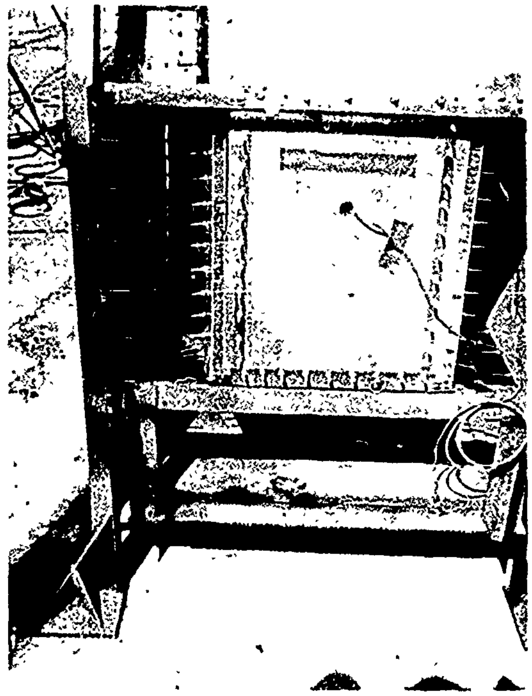

Figure 13. Damage to simulated AH-1 structure at projectile exit.

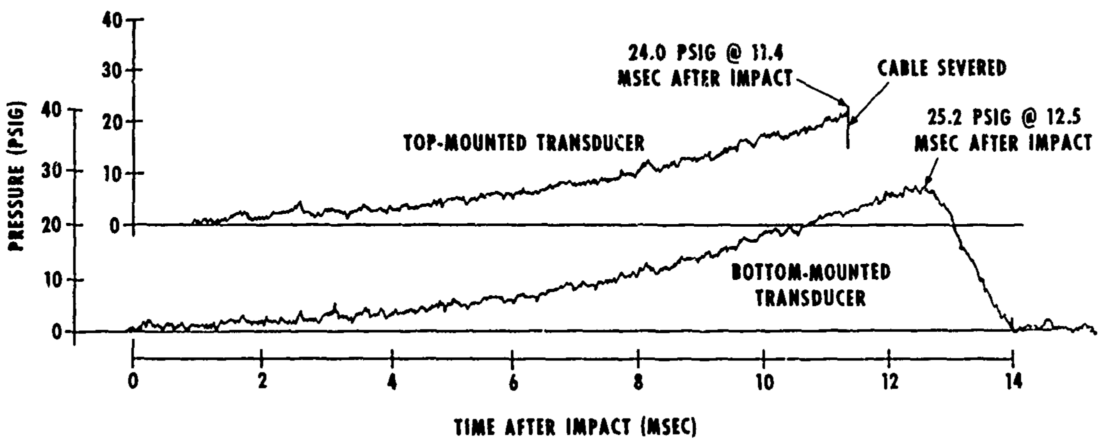

Figure 14. Pressure-time histories obtained during AH-1 fuel tank overpressure tolerance test.

MILITARY SPECIFICATION TANK TESTS

It was decided to use the available 30-inch by 30-inch by 24-inch crashworthy, caliber .50 self-sealing tank fabricated in accordance with MIL-T-27422B to obtain ullage over-pressure tolerance data under three conditions. First, tests were conducted with no structural support to determine the strength of the crashworthy bladder alone. Second, tests were conducted with Z-bar reinforced aluminum structure; third, AVCO Thermarest 5052 rigid foam was installed between the Z-bars to examine the effect of increasing structural support.

Fifteen tests were conducted using the various tank and structural configurations shown in Table 2.

Goodyear ARM-061A four-windowed cubes were used in the first nine tests in this series. The windows were attached with 1/4-inch-thick steel flanges. The window material was Goodyear ARM-063 in the first test, Firestone 1550-1E in the second test, and Goodyear ARM-061A in the remaining tests. Tests 10 through 15 were conducted using Goodyear ARM-063A cubes with no side windows and an oval top access hole. A plate was made to cover the top access hole of each tank, which permitted mounting of the vapor transfer and sample lines and a pressure transducer. A pressure transducer was also mounted in the right side of each tank.

Tanks Without Structural Support

The unsupported cubes were simply strapped to a table as shown in Figure 15. A 0.125-inch-thick 2024-T3 aluminum function plate was taped to the front. Figure 16 is a photograph of the test equipment positioned in the ballistic backstop.

The first two tests were conducted with fuel/air mixtures higher than stoichiometric, resulting in moderate pressure rises that did not cause tank failure. Considerable venting was observed from the top access ports and several windows. The steel flanges were bent slightly during each test. The fuel/air ratio was lowered for the next two tests, resulting in pressure rises that caused catastrophic damage. In test 3 the entire top access port was blown off (see Figure 17), and in test 4 the front of the tank tore across the entire tank width and the escaping gases had enough reactive force to overturn the tank and table (see Figure 18). The tear in this tank, as well as the severe flange bending that also occurred in this test, is shown in Figure 19.

Tests results are summarized in Table 2. Representative pressure-time histories are shown in Figure 20 for tests 1 and 4 Note that the higher fuel/air ratio resulted in a longer time to peak and a lower peak pressure. This trend agrees with that observed in Reference 3. There appears to be good agreement between both transducers. Both tank failures occurred in the vicinity of the window fitting, which did not provide a true indication of the basic bladder material strength.

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[3] Ferrenberg, Allan, and Blickenstaff, Joel, *Fuel Tank Non-Nuclear Vulnerability Test Program*, AFAPL-TR-74-83, Air Force Aeropropulsion Laboratory, Wright-Patterson Air Force Base, Ohio, February 1975.

TABLE 2. SUMMARY OF RESULTS - MIL-CUBE TESTS

Test No.	Configuration	Ambient Temperature (°F)	Ullage Temperature (°F)	Fuel/Air Mixture (volume % JP-4)	Pressure Rise (psig) T	Pressure Rise (psig) S	Time to Peak (sec)	Results
1	Unsupported crashworthy MIL-CUBE with four side windows	32	31	4.6	36.8	31.4	0.410	No damage
2		32	33	4.9	41.4	37.5	4.100	No damage
3		47	54	1.5	55.3	51.8	0.042	Top access port blew off; window frames bowed
4		54	63	1.5	55.3	41.6	0.034	Tank ripped entirely across front under window
5	Crashworthy MIL-CUBE supported with 3-inch Z-bar reinforced 0.063-inch-thick aluminum structure	62	58	1.0	32.0	*	0.150	Moderate Z-bar damage; tank undamaged
6		55	56	1.5	61.0	*	0.040	Moderate Z-bar damage; tank top access cover came loose
7		57	57	1.5	62.0	*	0.060	Moderate Z-bar damage; tank undamaged
8		61	65	1.5	61.0	*	0.045	Moderate Z-bar damage; tank undamaged
9		56	52	1.6	70.7	69.6	0.049	Z-bars flattened; tank ripped top and back near window
10	MIL-CUBE without windows and 0.090-inch-thick aluminum structure	73	75	1.1	68.0	*	0.039	Moderate Z-bar damage; top access cover came loose
11	Crashworthy MIL-CUBE supported with 3-inch rigid foam-filled Z-bar reinforced 0.090-inch-thick aluminum structure	70	72	2.0	54.0	*	0.091	Minor Z-bar bending; no tank damage
12		82	84	2.4	32.0	*	0.597	Same tank tested three consecutive times with only minor Z-bar damage and no tank damage
13		82	84	1.6	60.0	*	0.060	
14		82	84	1.2	61.0	*	0.071	
15		54	60	1.8	80.0	*	0.010	Tested with 23mm HEI-T; 4-inch-diameter entrance hole; minor damage

T = pressure reading from transducer in top of tank. S = pressure reading from transducer in side of tank.
* = lack of data indicates either line cut or transducer not installed.

Figure 15. Unsupported MIL-CUBE test tank prior to test.

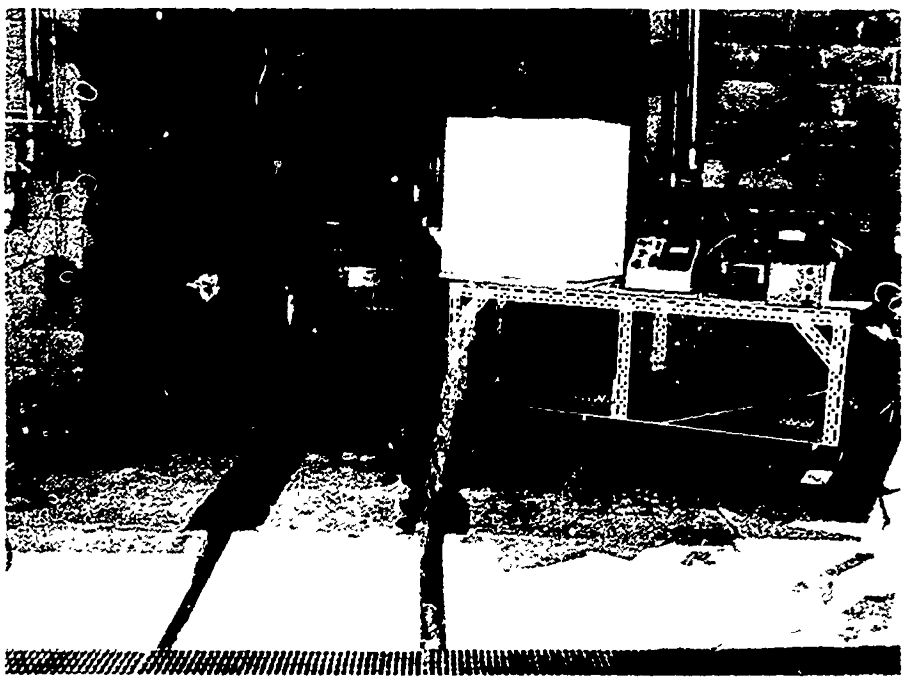


Figure 16 Unsupported MIL-CUBE test equipment at ballistic backstop.

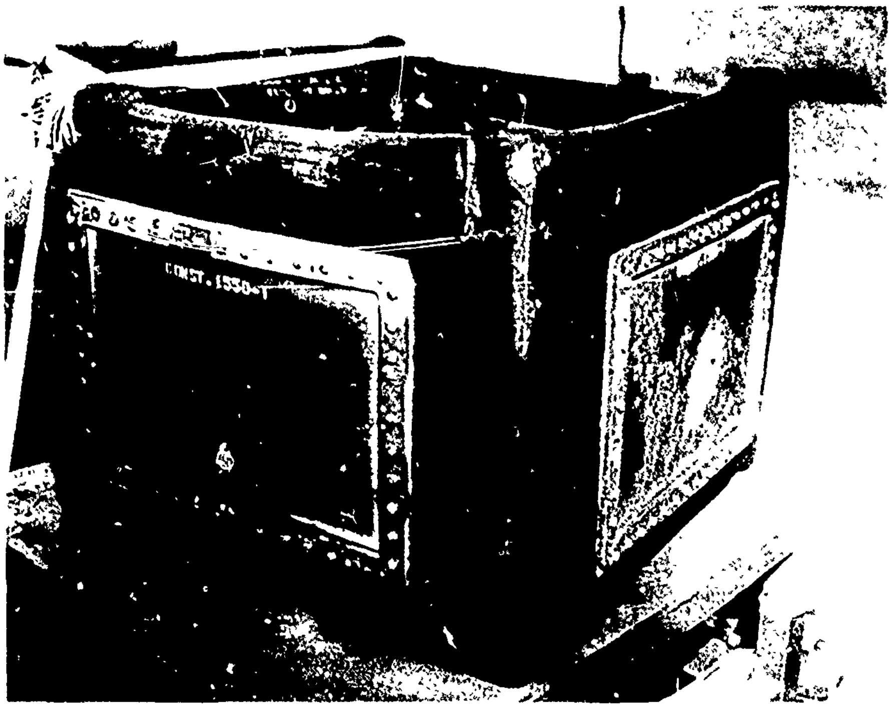


Figure 17. Damage resulting from MIL-CUBE test 3.

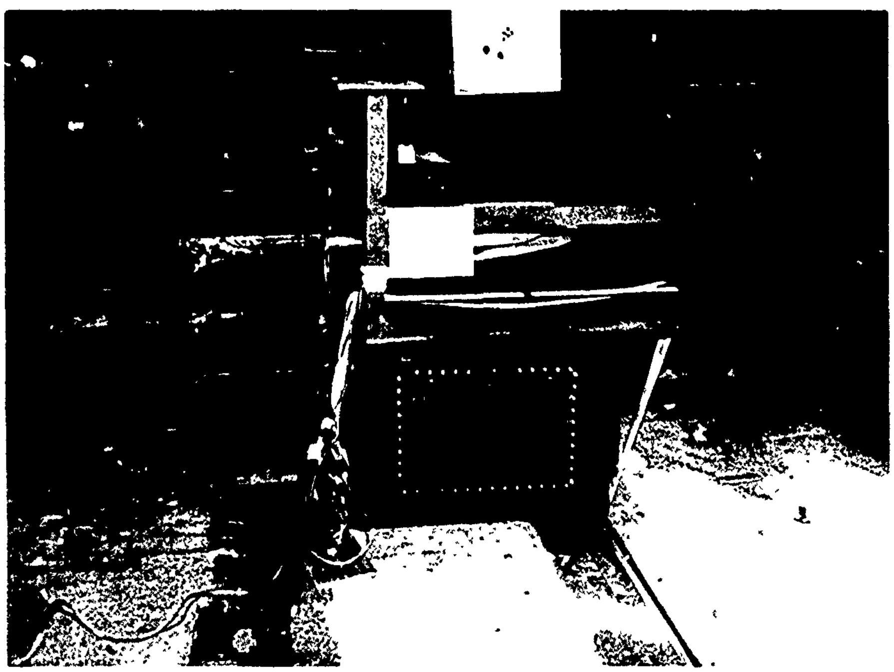


Figure 18. Tank overturned as a result of MIL-CUBE test 4.

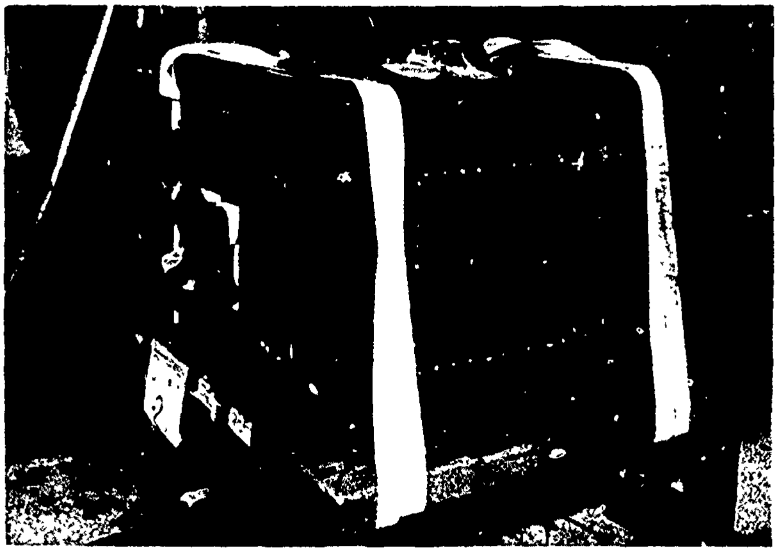


Figure 19. Tank damage resulting from MIL-CUBE test 4.

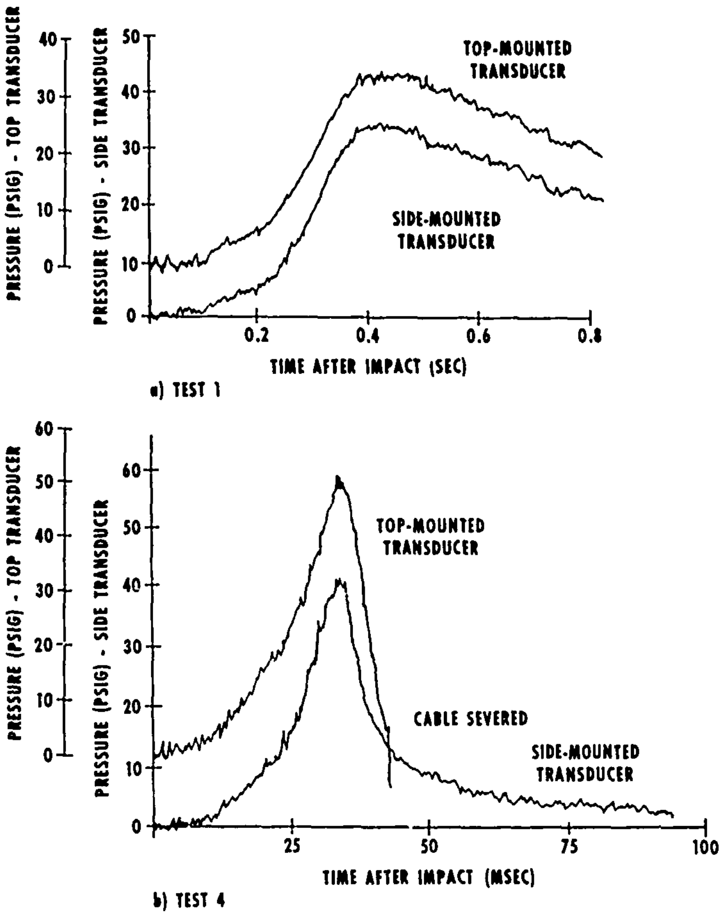


Figure 20. Pressure-time histories of MIL-CUBE tests 1 and 4.

Tanks With Structural Reinforcement

The fixture shown in Figure 21 allowed mounting of Z-bar reinforced aluminum panels on three sides of the tank. The bottom and one side were channel reinforced steel panels. The location of the vapor transfer and sample lines and instrumentation probes prior to testing is shown in Figure 22. The space above the tank was filled with Thermarest rigid foam during the actual testing. The aluminum panels were fabricated from 0.063-inch-thick 2024-T3 for tests 5 through 9 and from 0.090-inch-thick material for tests 10 through 15. In tests 11 through 15 the space between the Z-bars was filled with Thermarest rigid foam.

In test 5 the 32 psig pressure rise caused no tank damage and only moderate Z-bar damage. The Z-bars were slightly bent and a few rivets were popped (see Figure 23). The fuel/air ratio was increased for tests 6 through 8, resulting in pressure rises around 60 psig and increased structural damage as shown in Figure 24. The bladder itself was basically undamaged; however, the top cover and windows came loose and resulted in considerable venting during the pressure rise. In test 9 the pressure rise of about 70 psig caused the bladder to tear across the back as shown in Figure 25. In test 10, a 0.090-inch-thick aluminum structure was used and the 68 psig pressure rise resulted in less Z-bar damage (Figure 26). The cube, which had no side windows, failed at the top access cover (Figure 27). Tests 11 through 15 with Thermarest foam-filled 0.090-inch-thick Z-bar reinforced structure resulted in only minor structural damage and no bladder damage (Figure 28). Three consecutive tests, 12 through 14, were conducted on the same tank and the damage was limited to the entrance and exit holes.

Test 15 was conducted with 23mm HEI-T at an impact velocity of 2420 feet per second. The projectile had an MG-25 (delay) fuse, so detonation occurred after penetration as shown in Figure 29. The projectile was expected to detonate further into the tank; however, it may have been slowed by the relatively heavy aluminum structure, its impact point on the Z-bar, and the presence of rigid foam. Photographs of the damage are shown in Figure 30. The exit sides sustained damage from the large fragments, but the wider cone of smaller fragments did only minor damage. Most of these fragments were imbedded in the crashworthy tank material; only a few penetrated the entire structure. In spite of the high internal pressure generated by both the blast and subsequent combustion, there was only minor structural damage and no tank damage attributable to this failure mode. The pressure-time history for this test is shown in Figure 31.

Results of the MIL-CUBE tests with structural reinforcement are summarized in Table 2.

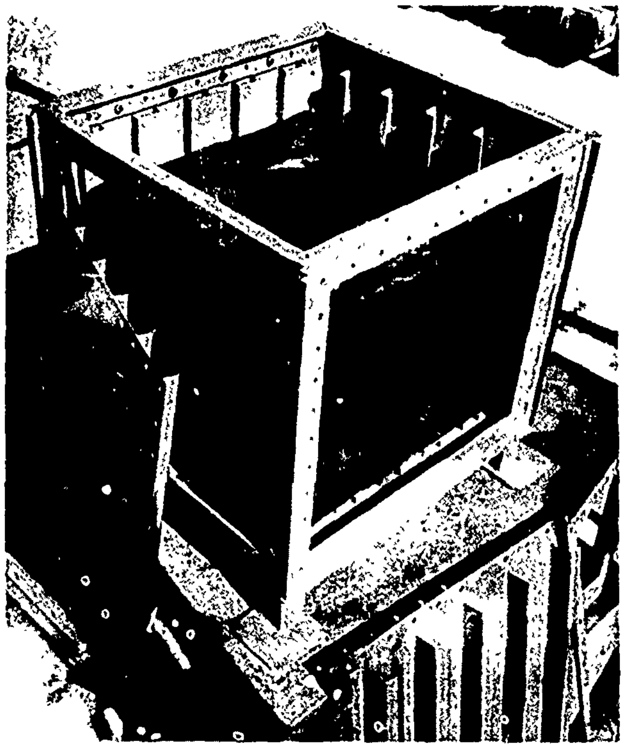


Figure 21. Fixture used in structurally supported MIL-CUBE tests.

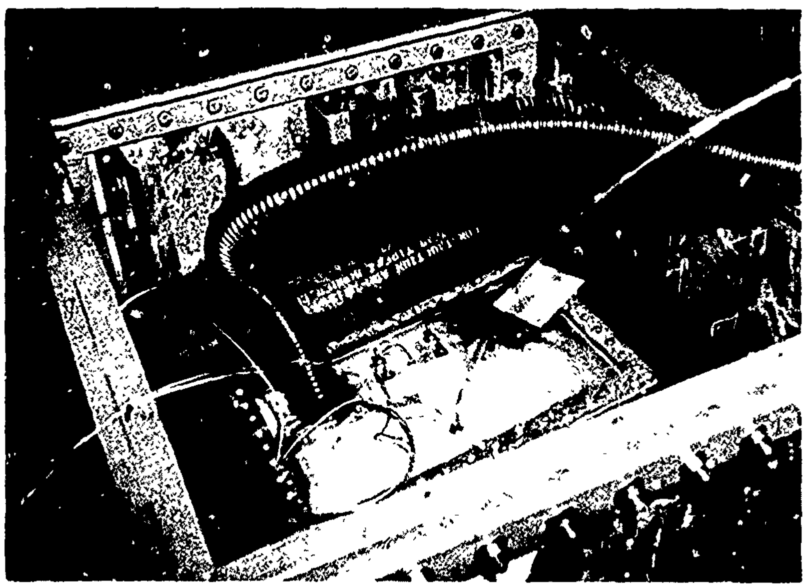


Figure 22. Location of vapor transfer and sample lines in supported MIL-CUBE tests.

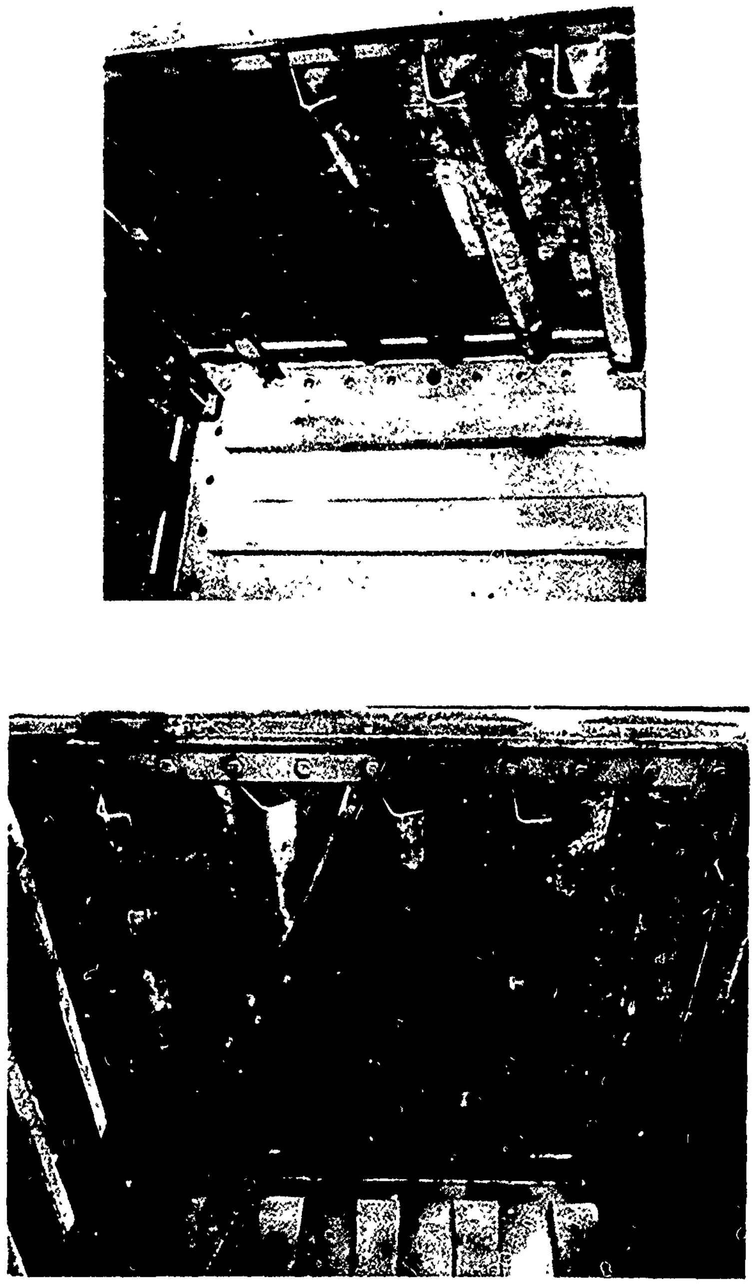


Figure 23. Structural damage resulting from MIL-CUBE test 5.

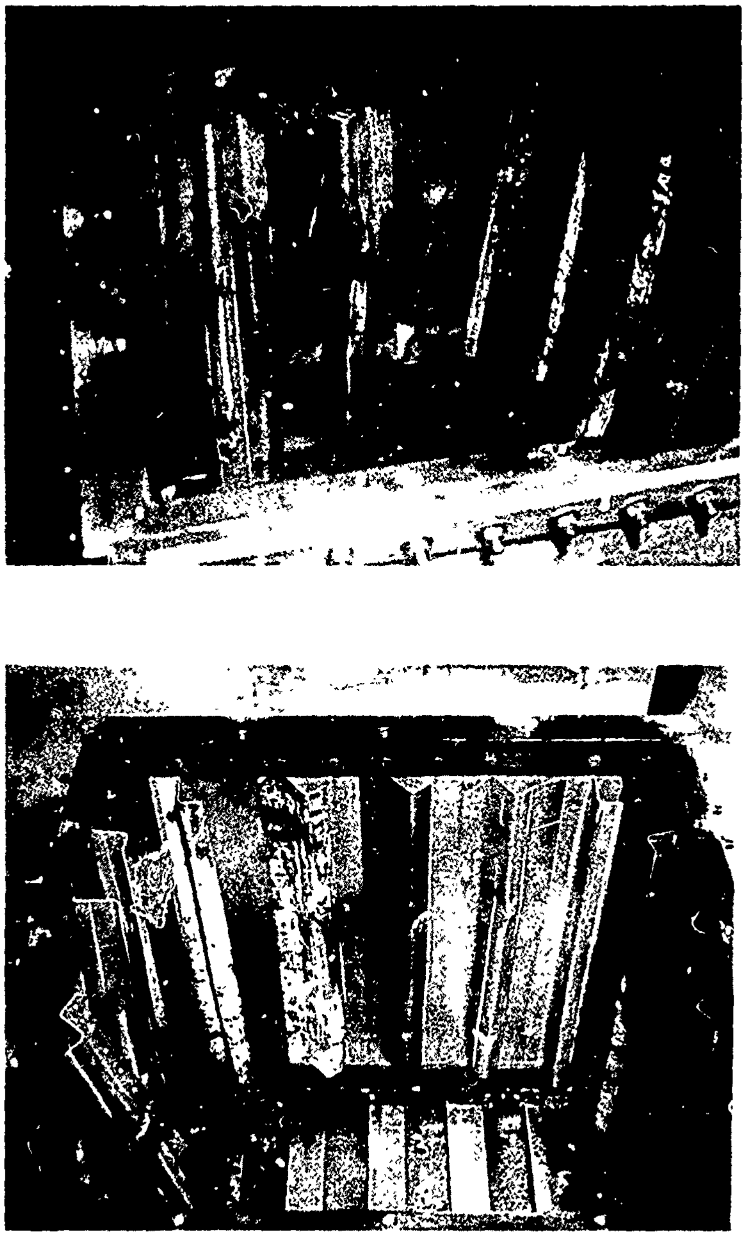


Figure 24. Structural damage resulting from MIL-CUBE test 6.

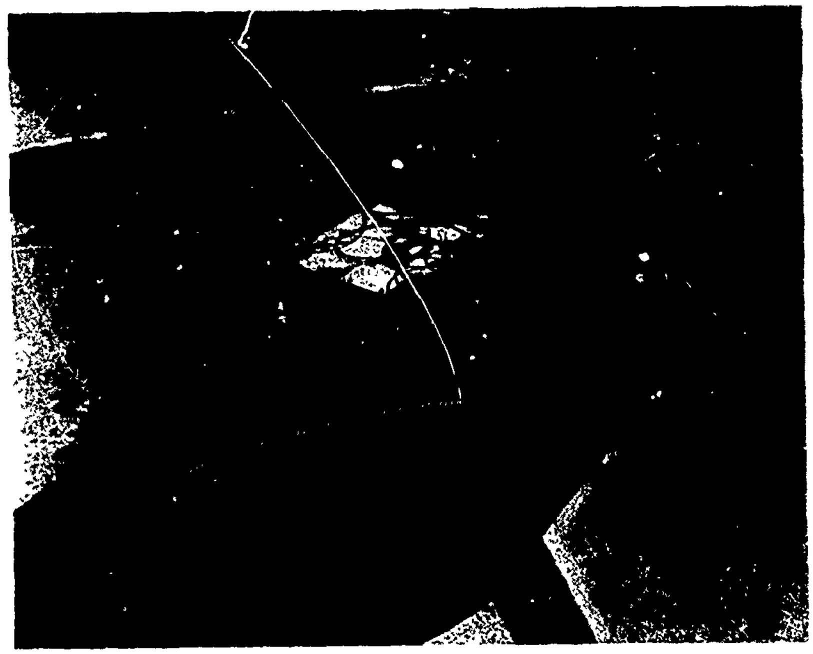


Figure 25. Bladder damage resulting from MIL-CUBE test 9.

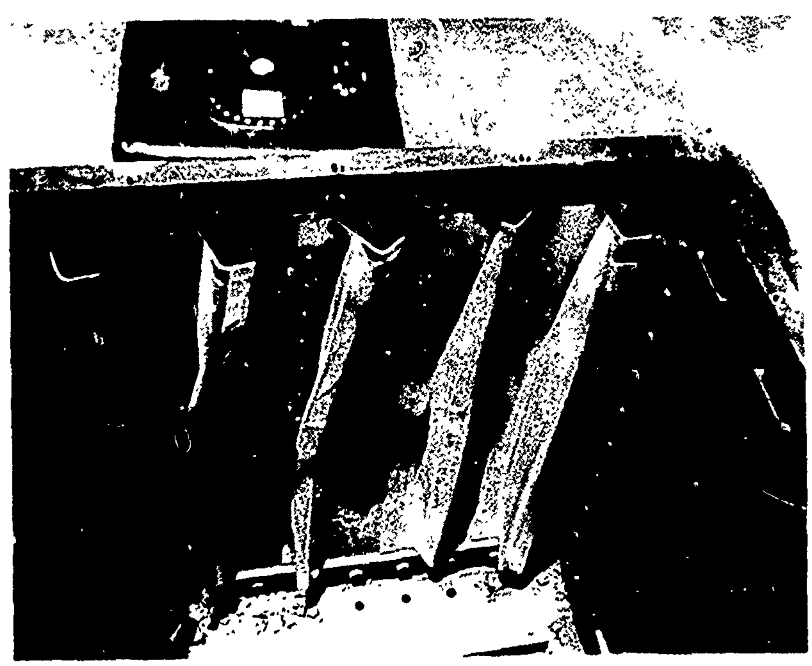


Figure 26. Structural damage resulting from MIL-CUBE test 10.

Figure 27. Access cover failure resulting from MIL-CUBE test 10.

Figure 28. Typical structural damage resulting from MIL-CUBE tests 11 through 14.

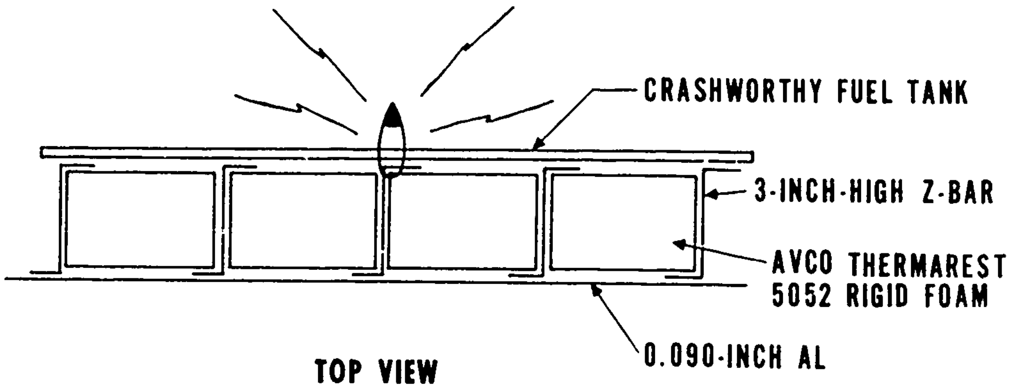
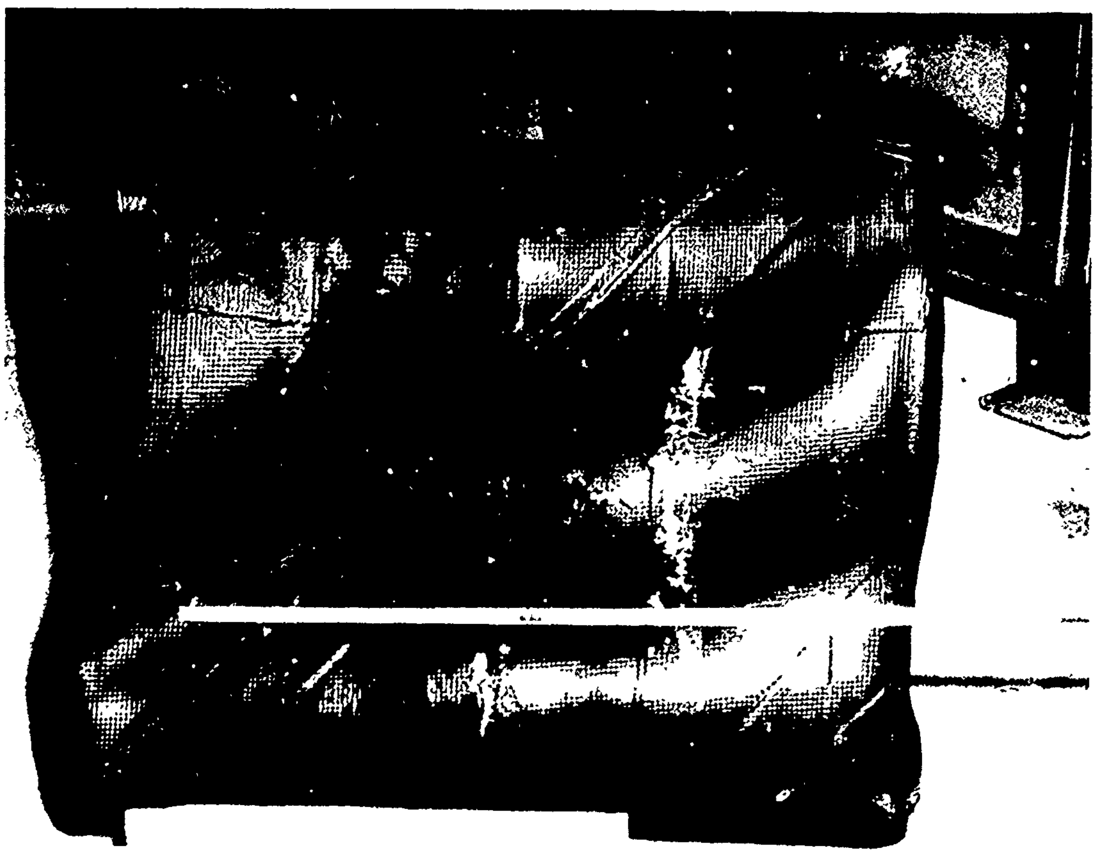
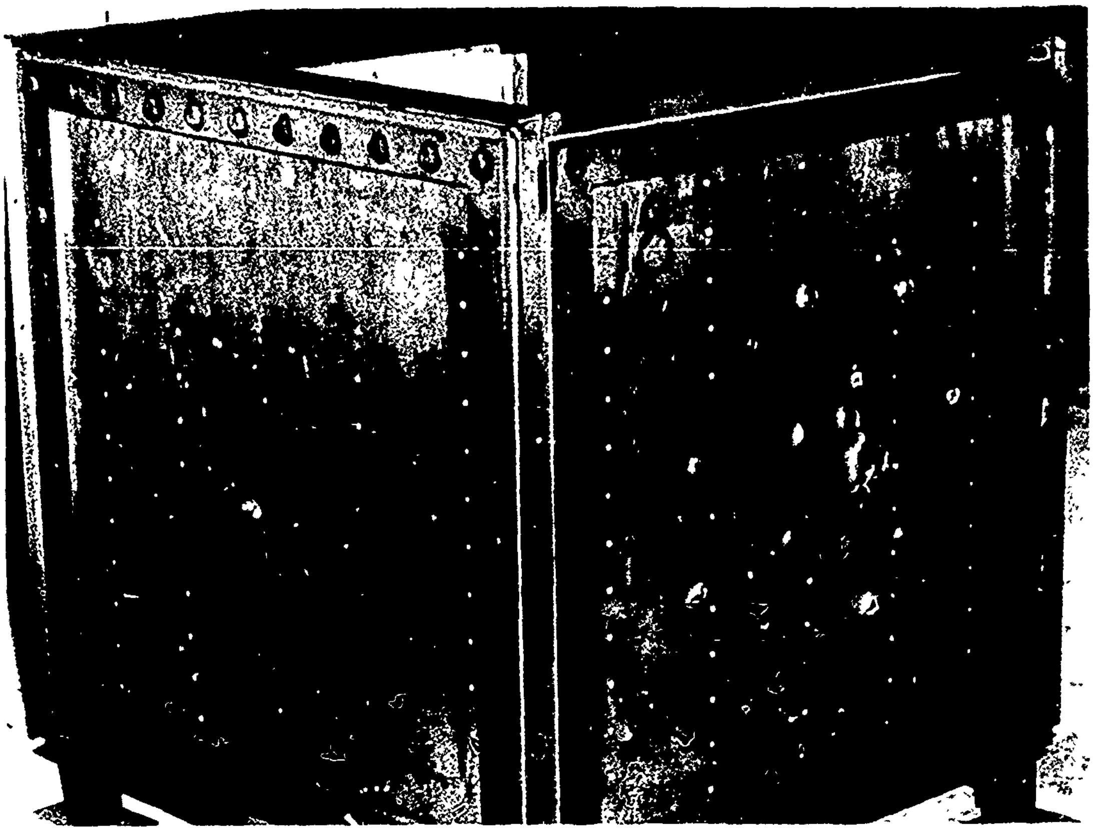


Figure 29. Sketch of 23mm HEI-T detonation location.



(a) Entrance hole in bladder

Figure 30. Damage resulting from MIL-CUBE test 15.



(b) Damage to structure, exit and right side

(c) Interior damage to exit panel

Figure 30. Continued.

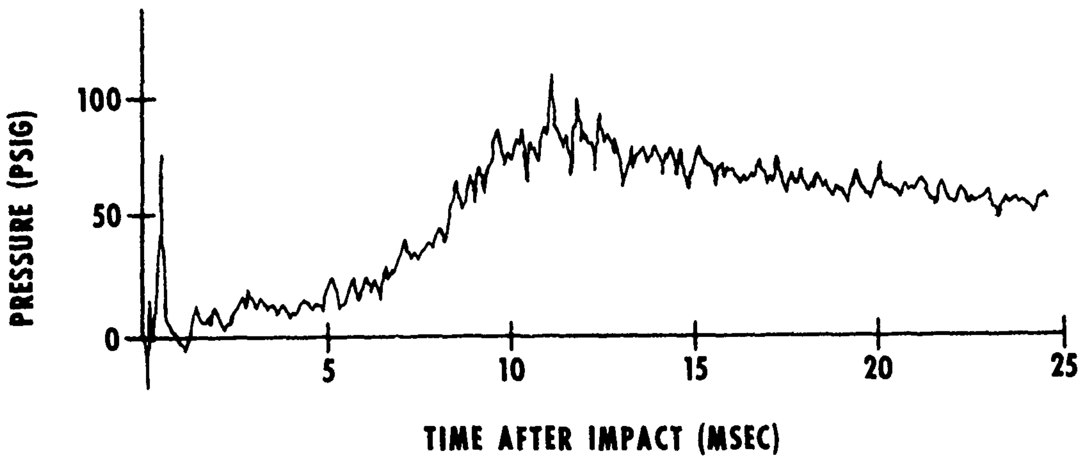


Figure 31. Pressure-time history of test 15.

UH-1H TESTS

The MIL-CUBE testing documented the toughness of the crashworthy tank material in tolerating internal dynamic pressures. Questions concerning the tolerance of the fuel system as a whole (including fittings and structure) will have to be answered in full-scale aircraft testing. As a first step in this area, a UH-1H crash-damaged fuselage with a complete, undamaged crashworthy fuel system and surrounding structure was prepared for testing. The fuel tanks were Goodyear ARM-061A.

Test of Upper-Right Tank

The filler cap in the upper-right tank was modified to permit injection of fuel/air vapors and mounting of a pressure transducer. Connections to the lower tanks were blocked. The tank was filled with a 1.5-percent JP-4 by volume mixture and impacted with a caliber .30 M1 incendiary through the outside wall at the middle of the tank. The resulting pressure-time history is shown in Figure 32.

The honeycomb structure on the front and rear of the tank was damaged as shown in Figure 33, but the tank itself was not damaged. The pressure rise was not as high as expected. Since the fore and aft walls of the cavity failed, expansion of the bladder could have reduced the pressure. Also, some pressure relief occurred through the vent.

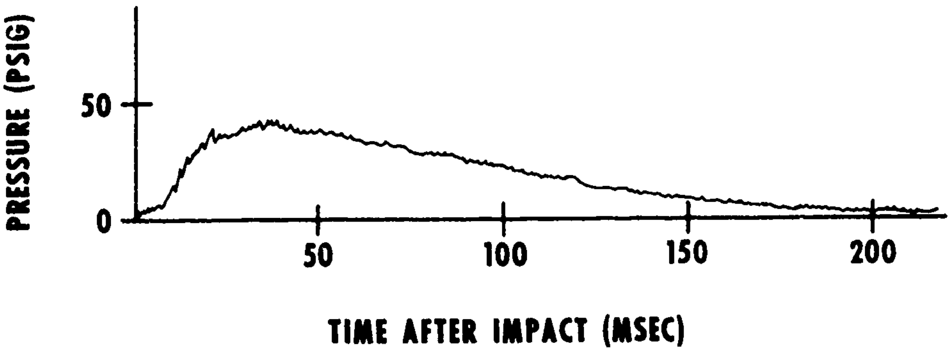


Figure 32. Pressure-time history of UH-1H tank (upper right).

(a) Forward panel

Figure 33. Damage to upper-right UH-1H tank structure.

(b) Aft panel
Figure 33. Continued.

Test of Upper-Center Tank

The installation access panel of the upper-center tank was modified to accept the vapor transfer tubes and a pressure transducer. The tank was filled with a 0.8 percent JP-4 by volume fuel/air mixture. Considerable difficulty was encountered in raising the mixture to the desired 1.5 percent. During test preparation, blocking of the bottom crossover lines was omitted and all three upper tanks were being filled with vapors. To compound the error the projectile aim point was incorrect, and the projectile went through both the center tank and the left tank, causing a mild explosion in both tanks. The pressure rise in the center tank was only 19 psig. Structural damage was limited to minor cracking of the honeycomb structure around both tanks. Neither tank was damaged. Further testing of the UH-1H was abandoned.

DISCUSSION OF RESULTS

The general criterion used to assess the damage was that if the bladder did not tear and no catastrophic structural damage occurred, the aircraft "survived." In these tests structural damage never appeared to reach the level that could be considered catastrophic; therefore, only those cases when the bladder itself failed were considered an aircraft "kill." In fact, in the UH-1H testing, the honeycomb panels began to fail at a low pressure, providing expansion volume for the bladder and thereby reducing the peak pressure and minimizing the opportunity for critical structural damage to occur.

Honeycomb structure of the type on the AH and UH helicopters began to incur damage at overpressure levels as low as 16 psig. If the tank within the structure was noncrash-worthy it failed at approximately 20-25 psig. The few tests of a crashworthy tank in a honeycomb structure failed to establish an overpressure threshold for this configuration. Tests to 42 psig without tank failure were conducted.

The reinforced aluminum structure sustained only Z-bar bending at pressure levels up to 60 psig. At 70 psig the Z-bars were almost completely crushed but the aluminum skin was not damaged. Increasing the aluminum thickness and filling the voids with rigid foam increased the structural strength to the point that pressure rises to 80 psig caused only minor damage. Crashworthy bladders installed in reinforced aluminum structure sustained pressure rises to 80 psig without tearing, whereas similar bladders failed at 50-55 psig when unsupported.

An important overall observation that can be made is that in spite of the fact that test conditions were designed to obtain maximum pressure reaction (i.e., a tank full with an optimum fuel/air mixture impacted at the center with a function plate attached directly to the tank), it was difficult to achieve a pressure rise in excess of 60 psig with an API ignition source. The pressure buildup seemed limited by both venting and bladder expansion. Peak reactions were obtained over a very narrow range of 1.5 to 1.8 percent JP-4. Concentrations only slightly outside this narrow band resulted in substantially lower pressure rise of about 32 psig. It could be inferred from this data that in the real world—where fuel/air mixtures are seldom optimum and where incendiary activation within the ullage is not automatic—the possibility of a catastrophic ullage explosion in Army helicopters is small.

The task of reducing ullage ballistic vulnerability has always involved various trade-offs of the degree of vulnerability reduction versus overall aircraft penalties. The results of these tests add a new dimension to that trade-off study. They show that the fuel tank itself has some inherent ullage explosion tolerance and that it is no longer necessary to design protection systems that completely eliminate the possibility of an explosion. Rather, the designer can determine the tolerance of a given fuel system and design a protection system (like a nitrogen inerting system) to provide protection only above that level, thereby minimizing parasitic system penalties. In fact, it may be possible using existing crashworthy tanks to build a helicopter fuel system that would simply tolerate any API-initiated ullage explosion and eliminate the need for other ullage protection.

CONCLUSIONS

It is concluded that:

1. Noncrashworthy bladder fuel tanks installed in typical honeycomb structure used in UH-1 aircraft have an ullage explosion overpressure tolerance of approximately 20 psig. One test of a crashworthy bladder in similar structure tolerated a 42-psig explosive overpressure.

2. Unsupported crashworthy bladders will tolerate ullage explosions up to 50-55 psig without tearing. Structural support for the bladder will increase its overpressure tolerance.

3. The possibility of a pressure rise exceeding 60 psig from an API-initiated ullage explosion in typical Army helicopter fuel tanks is small.

RECOMMENDATIONS

It is recommended that:

1. Trade-off studies to optimize the ullage explosion protection schemes for each aircraft be conducted which integrate such factors as bladder and structural configuration and inerting system requirements. A preliminary estimate of ullage explosion tolerance could be made using the data in this report subject to verification by ballistic tests on the actual aircraft.

2. A similar test program using 23mm HEI-T be conducted to obtain overpressure tolerance data for small HEI threats.

3. The small data base in this report be expanded with additional tests.